IV Conferencia Panamericana de END
Buenos Aires – Octubre 2007

AAENDE
Asociación Argentina de Ensayos No Destructivos y Estructurales

Inspecting tubes installed in heat exchangers with a special eddy current probe and single frequency

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Abstract

The integrity of tubes installed in heat exchangers are frequently checked using eddy current (ET) testing systems, connected to ordinary "bobbin-coil" probes. To eliminate the interference of ferromagnetic support plates, such systems operate simultaneously with two or more frequencies. This paper presents the development of a special ET probe that allows the inspection of non ferromagnetic tubes, installed in heat exchangers, using single frequency test systems, and strongly reducing support plates interference. Constructive details and photographs of probe prototypes are presented. The practical applicability and efficacy of the developed probe was verified at laboratory, using ASME compliant calibration standard tubes, containing artificially machined volumetric discontinuities. To simulate the presence of actual support plate a carbon steel ring was employed. Screenshots, taken from a suitable eddy current test system, connected to the developed probe and showing representative support plate and discontinuities corresponding signals were obtained and are also presented.

1. Introduction

Eddy current is an non-destructive test [1] based on the induction of electric currents on conductive materials, as shown in the Figure 1. It can be verified that an exciter coil generates a primary magnetic field which is responsible for the induction of eddy currents on the surface and sub-surface of the material. By their turn, such currents generate a secondary magnetic field which is opposition to the first one. The interaction of those two fields results a value for the complex impedance of probe coil, that can be measured by the inspection system. The generation of eddy currents depends on the exciting frequency and three factors related to the examined material: geometry, electrical conductivity (σ) and magnetic permeability (μ). The presence of flaws and other discontinuities or conductivity and/or permeability changes can be interpreted as non homogeneity of the material and will be directly responsible for the behavior of the induced currents. Consequently, they will interfere in the value of the complex impedance of the coil which may be analyzed.

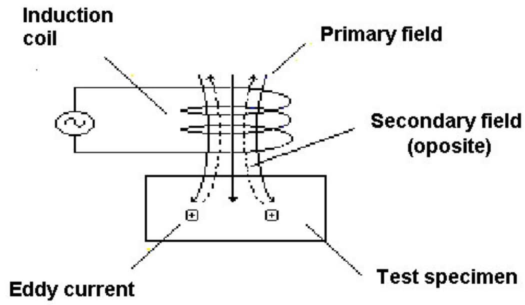


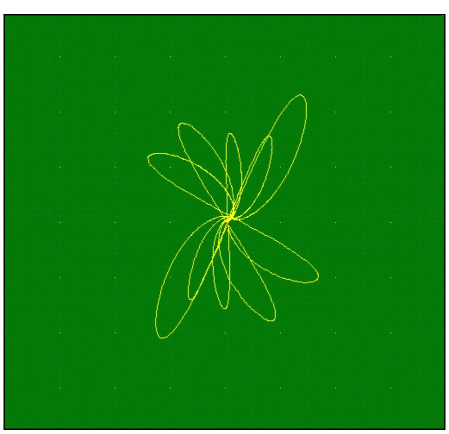
Figure 1 – Eddy current generation.

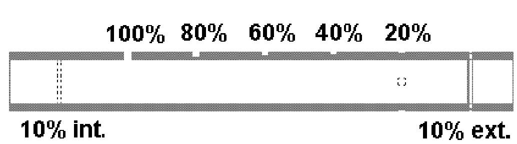
A basic inspection system can be assumed as an alternated current source that feeds, trough a power amplifier, the coil(s) of a testing probe, which complex impedance is constantly measured and displayed on the screen of a display instrument, usually a digital storage oscilloscope working in X/Y mode.

2. Tube inspection

2.1 Tube inspection using eddy current

Tube inspection is usually performed using bobbin coil probes operating in absolute or differential mode. The first one is useful in the evaluation of gradual discontinuities like wastage or wall thinning. Differential mode is most indicated to evaluate localized flaws. If tube internal diameter is to small and/or the tube is not installed, external probes may be employed. During the inspection, as the probe passes over a defective area, a corresponding indication is shown on the screen of the test equipment. In Figure 2a, five typical signals, obtained with internal differential probe, from a calibration reference standard [2] containing flat bottom holes (FBH), represented in Figure 2b are presented. Test frequency was set to 20 kHz. Note that the inclination (phase) of each *Lissajous* figure depends on the depth of a corresponding FBH. Evaluation of actual flaws is accomplished by means of phase x depth correlation curves.





a) **b)**

Figure 2. Typical *Lissajous* figures (a) and ASME reference standard tube (b).

2.2 Heat exchangers inspection

When inspecting tubes are installed in heat exchangers an inherent difficulty is the presence of support plates. Those structural components contain tents or cents of holes that guides and holds the tubes. They are generally constructed using ferromagnetic materials. So, when conventional bobbin coil probe passes near the plate/tube region, its impedance changes and a corresponding signal is plotted in the screen of the test system. Sometimes, the amplitude of such signal is so large that the electronic circuits of the test equipment may even saturate. If a discontinuity exists under or near a plate its detection, by means of single frequency bobbin coil probe, is almost impossible. To overpass that difficulty, dual frequency systems are widely employed [3]. As it can be seen in Figure 3, ET probe is fed simultaneously with two frequencies and the obtained signals are processed separately in two channels. Vertical (V) and horizontal (H) components of Channel # 2 are phase rotated, until the plate corresponding signal inclination matches that one verified in Channel #1. Then, V and H amplitudes are also adjusted. Finally the components are subtracted each other and the plate signal is canceled. For other signals no cancellation is accomplished. Nowadays, the process is performed by computer assisted systems. By other hand, the cost of such test system is large if compared to an ordinary single frequency unit.

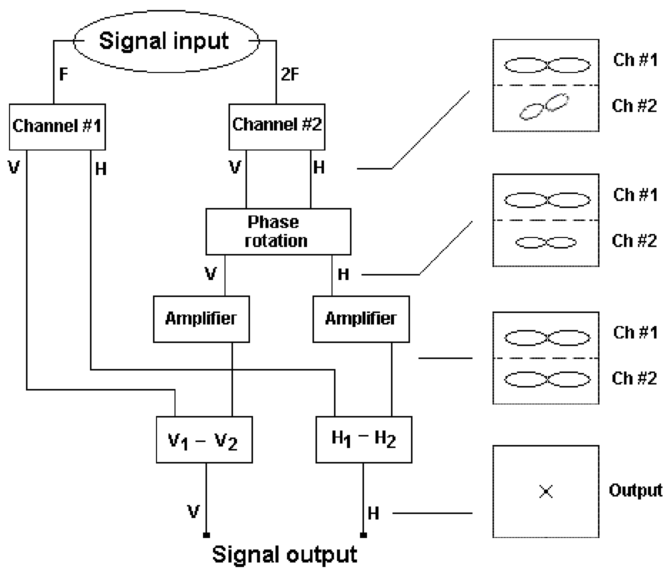


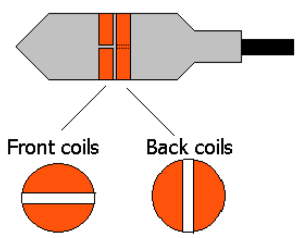
Figure 3. Plate signal dual frequency cancellation operating method.

3. Probe design

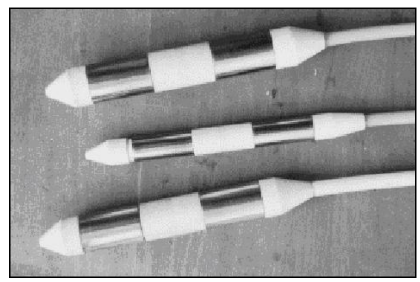
Many companies develop and commercialize ordinary bobbin-coil eddy current probes. Basically, an ordinary differential bobbin coil probe has two similar coils made of coated copper wire connected in differential mode. The diameter, width, number of turns and impedance of each coil depend on the application parameters such as tube material, internal diameter and wall thickness. This paper presents the development of a special probe, that allows the inspection of non ferromagnetic tubes, installed in heat exchangers, using single frequency test systems, and strongly reducing the interference of support plates. Many criteria can be adopted for the development of a customized probe. For this research, the strategy involves primarily the calculation of an optimum operating frequency that is calculated using the empirical formula [4]:

$$f_o = 10\,\rho \,/\, W^2 \tag{1}$$

Where f_o is the operating test frequency (Hz), ρ is the electrical resistivity of the tested material (μΩ . m), W is the cladding thickness (inches). Based on the tube dimensions, the external diameter of the probe may be determined, taking in account an adequate fill factor. As the test system output impedance is usually known (e.g. 50 Ω), a common approach is to impose that value, at f_o, for the probe coil impedance and then calculate the coil properties. As can be seen in Figure 4a, the probe is basically formed by four sensors resulting from the mechanical assemblage of two couples of semi-circular coils connected in differential mode. For each couple, both coils are always in the same tube section so, the sensitivity for surrounding discontinuities, such as plate supports, is intrinsically low. Couples are assembled axially rotated by 90° and separated by 3-4 mm. Figure 4b shows the final aspect of some developed probes.



a)



b)

Figure 4. Probe constructive concept (a) and prototypes actual aspect (b).

4. Results

4.1 Signal shape

Signal response of the probe differs from differential bobbin-coil. For a small discontinuity the detection will present typical absolute-mode behavior, but signal amplitude depends on its axial position. Maximum amplitude is obtained at 3:00, 6:00, 9:00 and 12:00 positions. Minimum amplitude is obtained at 1:30, 4:30, 7:30 and 10:30. Figure 5 helps to better understand the process. It can be observed that for 12:00 and 9:00 signals the aspects are very similar. For 1:30 position amplitude decreases.

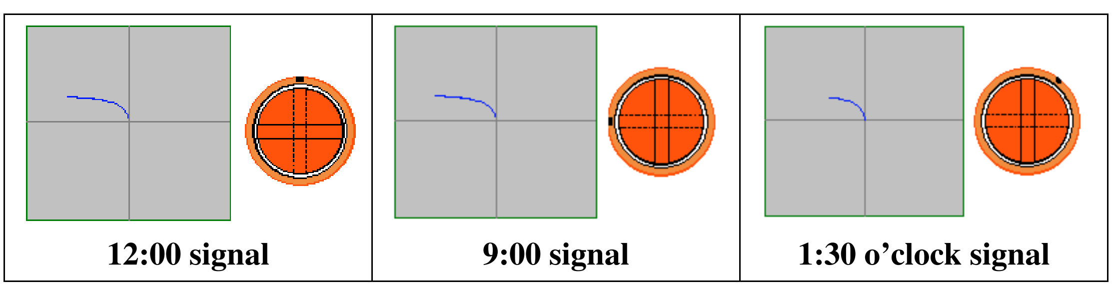
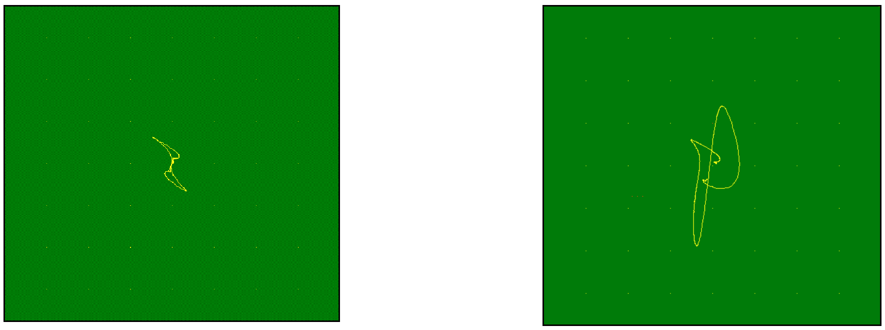


Figure 5. Depending on its position a flaw presents different signal amplitude.

4.2 FBH and support plate suppressed signals

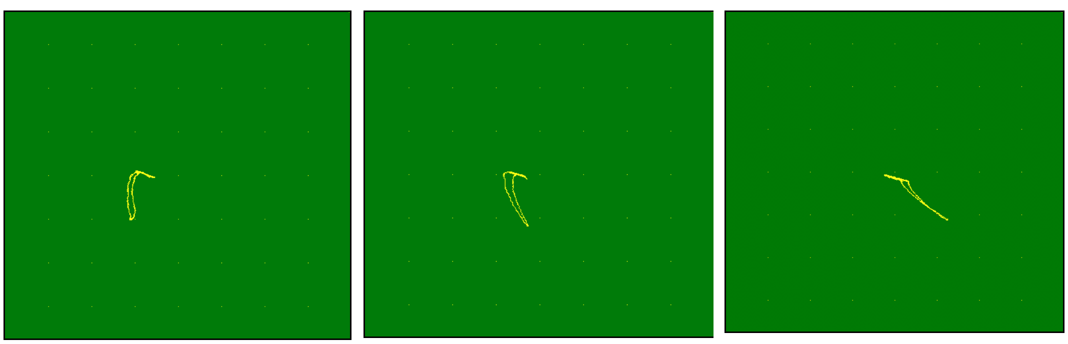
To demonstrate the probe performance including support plate signal suppression a set of screenshots was taken from a MAD8D ET system [5]. Inspected object was an 1.6 mm in thickness ¾' aluminum-brass ASME standard tube. A carbon steel ring was employed to simulate a support plate. Test frequency was set to 20 kHz. Figure 6a shows a typical support plate signal obtained with a conventional bobbin-coil probe. The distorted signal presented in figure 6b was formed by the 60% external FBH placed under the support plate.



a) **b)**

Figure 6. Signal generated by carbon steel ring (a). Signal obtained when that ring is placed over the 60% external FBH (b).

Figures 7a, 7b and 7c show 60%, 80% and 100% external FBH respectively. Figure 8 shows the signal formed by the support plate. Suppression may be is clearly observed.



a) **b)** c)

Figure 7. Signals for 60% (a), 80% (b) and 100%(c) external FBH.

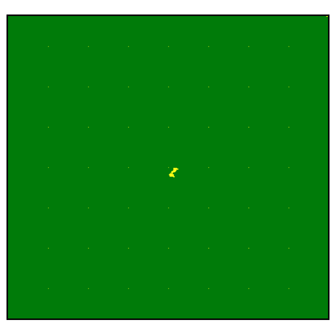


Figure 8. Support plate (suppressed) signal.

5. Conclusions

- The developed ET probe allows the inspection of non ferromagnetic tubes, installed in heat exchangers, using single frequency test systems;
- Obtained signals are typical absolute-mode *Lissajous* figures;
- Vibration lift-off noise level is some high, a expected characteristic of absolute probes;
- Detected discontinuities can be analyzed by means of phase criteria;
- Support plates interference was strongly reduced.

The authors intend to continue this research in future. The main goal is to develop differential probes which should present better vibration (lift-off) immunity.

References

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